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DEVELOPMENT OF A MULTI-PISTON BINDERLESS BRIQUETTING MACHINE

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ABSTRACT

Cooking and heating fuels needed for everyday survival is experiencing either dwindling supply, fluctuating prices or difficulty in accessing it, with developing countries being the worst hit, so the poor and low income earners rely greatly on fuelwood to meet their everyday energy needs. Agricultural waste residues can be a reliable alternative to fossil fuels and fuelwood when converted into solid fuels called briquettes, whose quality is determined by the production factors. In this research, a multi-piston binderless briquetting machine was designed, fabricated and tested by producing briquettes from selected biomass wastes (corn cob, sugarcane bagasse, groundnut shell, sawdust and rice husk) and polyethylene wastes (sachet water wastes), using the machine. Experimental run was designed via Taguchi fractional factorial using Minitab 17 software, for 27 runs orthogonal array. Input factors; moulding temperature (250, 270 and 290 ^{0}C), Moulding pressure (46, 56 and 66 MPa), composition of polyethylene (10, 20 and 30%) and dwell time (60, 180 and 300 seconds) were varied. From the analysis of the materials and briquettes produced, highest bulk density of the mixed material was 250kg/m^3, highest compressed density of the briquettes was 587 kg/m^3, highest relaxed density was 545 kg/m^3 while highest calorific value was 26.3162 MJ/kg. For proximate analysis, lowest moisture content of the briquettes was 0.04%, lowest volatile matter was 71.63%, lowest ash content was 2.77% and highest fixed carbon was 20.40%. Fuels produced from these selected materials were fuels of good qualities that can provide alternative to fossil fuels and fuelwood.

Keywords: Biomass residues, polyethylene waste, fuelwood, briquettes, briquetting machine, binder

INTRODUCTION

Energy is essential for heating and cooking for continuous human existence and the sustenance of life and it is said to be key for sustainable development of any nation (Amigun *et al*., 2008). But continuous shortage in energy supply has resulted in high deforestation as about half the world's population rely on fuelwood for cooking, and energy crisis is brewing as access to fuelwood is becoming more difficult and supply is dwindling by the day (Gujba *et al*., 2015; Chaney 2010; Chaney *et al*., 2009). Agricultural biomass waste residues are available as alternatives to fuelwood but they burn too fast when utilised to cook food which requires an extended heating time and constant heat release therefore, fuelwood has continued to remain the energy source of choice for low, medium income earners and rural dwellers (Chaney *et al.*, 2009). Also, the use of biomass residue in their natural form as fuels have disadvantages such as; being bulky, having uneven and irregular shape and sizes, low density, low energy density and fluctuating energy output, low heating value in a unit volume, high moisture content, very low thermal efficiency, excessive amount of smoke they generate and widespread air pollution and these make them difficult to handle, store and transport (Orisaleye *et al*., 2022; Tamilvanan, 2013; UNEP, 2013; Maninder *et al.*, 2012; Chaney *et al.*, 2009; Grover and Mishra, 1996). These setbacks are overcome through briquetting which involves the compaction of loose biomass residue into regularly shaped homogenous solid fuel called briquettes which have better characteristics compared to the materials in their original form, improves handling characteristics and make their transportation more easy, improves volumetric heating value compared to the base material and then burn rate can be controlled (Kaur *et al.*, 2017; Bhoumick *et al.*, 2016; Akowuah *et al.*, 2012; Emerhi, 2011; Chaney *et al.*, 2009; Kaliyan and Morey, 2009). Compressed materials into solids of diameter equal to or larger than 30 mm are referred to as Briquettes (Sitthipong *et al*., 2020), while those with diameter less than 30mm are referred to as Pellets. According to Sani (2008), briquettes have 6 to 7 times higher energy per kilogramme than its base material.

Several briquetting machines have been developed by researchers to produce briquettes from different combustible waste materials. Abdullahi (2022) developed a low cost briquetting machine that produced briquettes from rice husk and sugarcane bagasse. The machine was based on power screw concept technique where power is transferred by the motor which rotates the machine's screw shaft via the V-belt. Okwu and Omonigho (2018) developed a simple, movable, light weight briquetting machine for bio-briquettes production and water hyacinth plant (WHP) and saw dust (SD) were the biomass waste materials utilized, using cassava starch as binder. Okwu *et al*. (2016) developed a briquetting machine producing briquettes from water hyacinth plant and waste paper, corn and cassava starch were the binders utilised. Darekar *et al*. (2017) designed and fabricated briquettes making machine operated by a 3tonnes hydraulic jack which compresses and punch in the downward direction, adopting 30 seconds dwell time to produce completely solid briquettes from sawdust and corn starch. Agidi *et al*. (2017) developed a hydraulically operated machine for making briquette from agricultural wastes, which converted rice husk, saw dust and sugar cane bagasse to briquettes. Ajieh *et al*. (2016) designed a briquette making machine driven by a 1hp electric motor, having a 20 mm diameter shaft driving the grinding plate. Dynamic load on the bearing was 8.9 kN and diameter of the screw shaft which was basically the briquetting screw press, was 40.8 mm. The dynamic load on the bearing was 11.42 kN and 7 hp electric motor power was required to transport, densify and eject the briquetted fuel from the machine. Ndideng *et al*. (2015) designed and fabricated multi-piston press, the fabricated machine was used to produce briquettes from pure husk and husk–bran mixtures. Ajayi and Osumune (2013) designed a briquette making machine with a single die extrusion press powered by a 3 kW, 1440 rpm electric motor driving the screw shaft at 480 revolutions per minute (rpm), to produce briquettes from sawdust and had production capacity of about 95 kg/hr.

In the literatures reviewed, no researcher combined the five biomass residues selected, with polyethylene in a designed experiment to produce briquettes in the absence of external binder. This work was aimed to develop a multi-piston binderless briquetting machine, to study effects of varying briquettes production factors which influence the quality of briquettes in order to control them and to produce briquettes of acceptable qualities. A multi-piston briquetting machine was designed, fabricated and tested, using equal combination by weight percent of agricultural biomass residues (corn cob, rice husk, sugarcane bagasse, groundnut shell and sawdust) with polyethylene wastes (sachet water wastes) as additives to improve the calorific value of the biomass-polyethylene blend briquettes.

MATERIALS AND METHOD

Materials

The materials selected for fabrication of the mould included mild steel sheet, cylindrical pipe, solid iron rod, angle iron, pressure gauge, electrical heater bands, contactor, miniature circuit breaker, heater wire, thermocouple, temperature controller, hydraulic jack, tension helical spring, bolts and nuts. While the materials employed in briquettes production to test the machine include corn cob, rice husk, sawdust, sugarcane bagasse, groundnut shell and polyethylene wastes. The mild steel materials used in the fabrication were purchased at building material market, Goodluck Jonathan way, Minna, Niger State, the solid iron rod and cylindrical pipes were purchased at scrap metal market Sabon gari, Minna, Niger State. The electrical components and pressure gauge were purchased at TR Integrated ventures, Ibrahim Taiwo road, Ilorin, Kwara State. Sugarcane bagasse was processed at Central workshop, Mechanical Engineering Department, Federal University of Technology, Minna, Niger state. Corn cob and groundnut shell were processed at Institute of Technology (IOT), Kwara State Polytechnic, Ilorin, polyethylene waste were processed at a packaging nylon production factory in Ganmo area, Ilorin Kwara State, Rice husk and sawdust needed no size reduction. The six different materials used in the briquettes production were sieved to the required particle sizes at the Civil Engineering Laboratory, Federal University of Technology, Minna, Niger State.

Design considerations

Briquettes have diameter equal to or larger than 30 mm (Sitthipong *et al.*, 2020). Cylindrical pipe of internal diameter 76 mm which will automatically be the external diameter of the briquettes to be produced, was selected. The external diameter of the pipe was 90 mm and pipe thickness is 7 mm.

In the classification of briquetting process according to pressure applied, medium pressure range is between 5 - 100 MPa (Marreiro et al, 2021; Kaur *et al*, 2017). It is possible to produce briquettes without adding binder materials only at elevated temperatures of 250 - 300 °C, employing high pressure (Kaliyan and Morey, 2009). Binderless briquetting mechanism utilising lignin in biomass material requires elevated temperature of about 160 ^{0}C to 280 ^{0}C and pressure between 4 MPa – 60 MPa according to Oyelaran *et al.* (2015) Onuegbu *et al*. (2012), depending also on the material used. Therefore, 250 – 290 ^{0}C temperature range was chosen for this study while pressure range was 46 – 66 MPa. Maximum working pressure for the design was set at 70 MPa. Electrical heater bands available were in range of Q 60 × 60, 100 w; Q 80 × 80, 1800 w; Q 100 × 100, 2400 w. Q 80 × 80, 1800 w was adopted so it can wrap round the 90 mm diameter pipe used as moulding chamber.

Design analysis of the multi-piston binderless briquetting machine

Determination of the volume of moulding chamber

The moulding chamber was a thick cylindrical pipe cut to size and welded to the top plate which seats the cover of the machine, the inner diameter, outer diameter and length of the moulding chamber were 76 mm and 90 mm 110 mm respectively. A centre solid rod of diameter 19 mm was provided to create central hole in the briquettes, diameter of the rod was the internal diameter of the briquettes. The moulding chamber which house the material to be densified was made to have height of 100 mm by arranging the piston head 10 mm above the bottom end of the cylinder, when the movable plate which carried the pistons was at rest (bottom end) on stoppers. The height to be occupied by the densification material was therefore 100 mm, and the internal diameter of the moulding chamber was the external diameter of the solid fuel formed.

The volume of the moulding chamber was calculated using the formula in equation 1, by modifying the one given by Ibitoye *et al*. (2023) as,

$$V = \frac{\pi(D-d)^2 h}{4} \quad (1)$$

Where V is the volume of the mould in m^3, d is the internal diameter of the moulding chamber in m and h is the height of the moulding chamber in m.

Substituting D=76 mm (0.076 m), d=19 mm (0.019), h=100 mm (0.1 m) and π=3.142, gives

V=0.0002552 m^3

The moulding machine is designed to produce eight (8) briquettes per batch. Therefore, total volume of the briquetting mould becomes;

$$V_T = 8 \times V \quad (2)$$

Substituting V=0.0002552 m^3 into equation 2 gives;

V_T=0.002042 m^3

The most commonly used mild steel is A36 grade mild steel type due to its low cost and ease of fabrication. It also has excellent strength, weldability and ductability. It has Yield strength of 250 MPa and Ultimate tensile strength of 400 MPa – 550 MPa. Taking the maximum value of the ultimate tensile strength and taking safety factor of 5, the allowable stress δ is calculated by the relation given by Ibitoye *et al.* (2023) as;

$$\delta = \frac{t}{f} \quad (3)$$

Substituting δ=550 MPa and f=5 gives δ=110 MPa

Determination of Circumferential or Hoop stress, Longitudinal stress and Maximum shear stresses

Cylindrical pipes under pressure fails due to either circumferential (hoop) stress or longitudinal stress acting on the internal walls of the pipe. The circumferential (hoop) stress and the longitudinal stress were given by Khurmi and Gupta (2005) as;

$$\delta tc = \frac{\text{P}\times\text{d}}{2t} \quad (4)$$

$$\delta tl = \frac{\text{P}\times\text{d}}{4t} \quad (5)$$

Where;

δtc – Circumferential or hoop stress for the material of the cylindrical shell

δtl – Longitudinal stress for the material of the cylindrical shell

P – Intensity of internal Pressure

d – Internal diameter of cylindrical shell

t – Thickness of the cylindrical shell

Substituting P=70 MPa, d=76 mm and t=7 mm into equations 4 and 5 gives, $\delta tc = 380\ MPa$ and $\delta tl = 190\ MPa$.
Maximum shear stress is one-half the algebraic difference of the maximum and minimum principal stresses (Khurmi and Gupta, 2005). Since the maximum principal stress is the circumferential stress (δtc = 380MPa), and the minimum principal stress is the Longitudinal stress (δtl= 190 MPa) therefore maximum shear stress is calculated from equation 6 as;

$$\tau_{max} = \frac{\delta tc - \delta tl}{2} = \frac{380-190}{2} = 95\ MPa \quad (6)$$

2.3.3 Piston design

The Piston was made from a cylindrical pipe and a welded plate (head), the entire piston was welded to the mid-plate (movable plate). There was clearance of 1 mm between the piston head and the inner diameter of the moulding chamber (sleeve) to reduce friction and enable free movement of the piston during densification. The piston was made from mild steel pipe of inner diameter, outer diameter and length of 39 mm, 45 mm and 140 mm respectively, while the piston head has inner diameter, outer diameter and thickness of 21 mm, 73 mm and 8 mm respectively.
Deflection of the piston due to buckling, the moment of inertia were calculated using the relation given by Singh (2011) as;

$$K = \sqrt{\frac{I}{A}} \quad (7)$$

$$I = \frac{\pi}{64}(D^4 - d^4) \quad (8)$$

$$A = \frac{\pi}{4}(D^2 - d)^2 \quad (9)$$

Where K is radius of gyration, I is moment of inertia, A is cross-sectional area of the piston, D and d are outer and inner diameter of the piston pipe in mm respectively.
Substituting values of D=45 mm, d=39 mm gives,
A=395.892 mm^2 from equation 9, I= 87739.5645 $kgmm^2$ from equation 8 and K=14.8871 mm from equation 7 respectively.

Hydraulic jack and pressure gauge selection

A 15 tonnes hydraulic jack was selected for this work because the pressure of a 10 tonnes hydraulic jack was calculated and the value fell short of maximum pressure value needed for this research. The pressure for a 15 tonnes hydraulic jack is calculated from the relation;

$$P = \frac{F}{A}, F = mg \text{ and } A = \pi r^2 \quad (10)$$

Where P is maximum pressure generated by the hydraulic jack, F is hydraulic force, A is cross sectional area of the hydraulic jack piston head, m is mass, r is radius of hydraulic jack piston head and g is acceleration due to gravity (9.81 m/s^2) as given by Ibitoye *et al.* (2023).
Diameter of the hydraulic jack piston head by measurement is 38 mm, the radius, r = $\frac{d}{2}$, =19 mm.
m = 15 ton =15000 kg
Substituting r = 25 mm, π = 3.142, g = 9.81 m/s^2, m = 15000 kg into equation 10 to obtain the value of A and F and then using the values of A and F to obtain P gives; A = 1963.75 mm^2, F = 147150 N and P = 75 N/m^2 (75 MPa)
From the maximum pressure calculated for a 15 ton hydraulic jack, it was appropriate for the maximum working pressure the range of pressure of 66 MPa for briquettes production in this research, pressure gauge having maximum value reading of 70 MPa was therefore selected for use on the hydraulic jack.

Design of Moveable (Mid-plate) and Base (Bottom) plates

The hydraulic jack sits on the base plate, when actuated, the hydraulic jack moved the moveable plate and piston to exert pressure on the materials in the moulding chamber thereby densifying the material. Equal stresses were acting in different direction on the moveable and base plate at the same time. The thickness of the moveable and base plate must overcome the maximum bending stress exerted by the hydraulic jack. Thickness and maximum deflection were determined using the relation given in equations 11 and 12 by Ibitoye *et al.* (2023) as;

$$t = \sqrt{\frac{1.5P}{\pi\sigma_m}\left[(1 + \upsilon)\ln\frac{2b}{\pi e} + 1 - k_2\right]} \quad (11)$$

$$y_m = k_1 \frac{pa^2}{Et^3} \quad (12)$$

Where a=length of plate (mm), b=breadth of plate (a=b for a square plate), P is concentrated load (N), υ is Poisson's ratio, E is Young's modulus ($N{\cdot}mm^{-2}$), t is plate thickness (mm), e is radius of area with force applied (mm), σ_m is maximum stress ($N{\cdot}mm^{-2}$), k_1 and k_2 are constants and y_m is the maximum deflection (mm). The moveable and base plates have 400 × 400 mm dimensions; therefore, $\frac{b}{a}$ = 1, k_1 and k_2 are constants with values 0.127 and 0.564, respectively. Poisson ratio, Young modulus, and ultimate tensile strength of mild steel are 0.303, 200 GPa, and 400 MPa, respectively. Radius of contact head of the hydraulic jack was 19 mm as measured. Concentrated load which is the hydraulic force, is 147150 N. Substituting the value into equation 11 gives the value of $t = 64\ mm$ and from equation 12, $y_m = 0.0570\ mm$.

Return spring selection

The return spring pulls back the movable plate to rest position and the piston head to the bottom of the moulding chamber after briquette production was completed, and makes it ready for the next cycle of production. According to Shigley and Mischke (2003), the spring index, C for most springs range from about 6 to 12. Table 1 is a guide for the selection of appropriate spring for given stress range.

Table 1: Preferred Range of Torsional stresses due to initial Tension for steel Helical Extension springs

Index C	Stress Range MPa
4	115 – 183
6	95 – 160
8	82 – 127
10	60 – 106
12	48 – 86
14	37 – 60
16	25 – 50

$C = \frac{D}{d}$ (13)

Where C= spring index
D= Helix spring diameter
d = wire diameter
Shigley and Mischke (2003).

From the table above, spring with index 12 was selected because it has the closest range for the maximum operating pressure of the research (66 MPa).

Contactor and Miniature Circuit Breaker (MCB) selection

Power is expressed in equation as given by Hewitson *et al.* (2004) and Ikechiamaka *et al.* (2023) as;

$P = IV$ (14)

Where P – Power in watts
I – Current in amperes
V – Voltage in volts
Number of band heaters = 8
Power rating of each band heaters = 1800 w
Power rating for 8 number band heaters = 1800 × 8 = 14400 W
V = 240 v

Rearranging equation (4) and substituting the above values,

$I = \frac{P}{V}$ = 60 Ampere (15)

Based on the value of current calculated, 100 A contactor and 63 A Miniature circuit breaker (MCB) were selected for use on the mould which were higher than the calculated current value.

Hinged on the design calculations the multi-piston binderless briquetting machine was fabricated. Its isometric and orthographic views are shown in figures 1 and 2 respectively and the pictorial view is shown in figure 3,

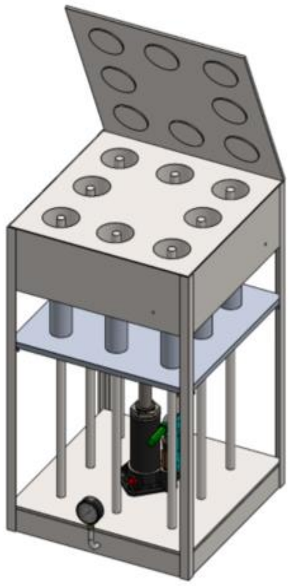

Figure 1: Isometric view of the developed multi-piston binderless briquetting machine

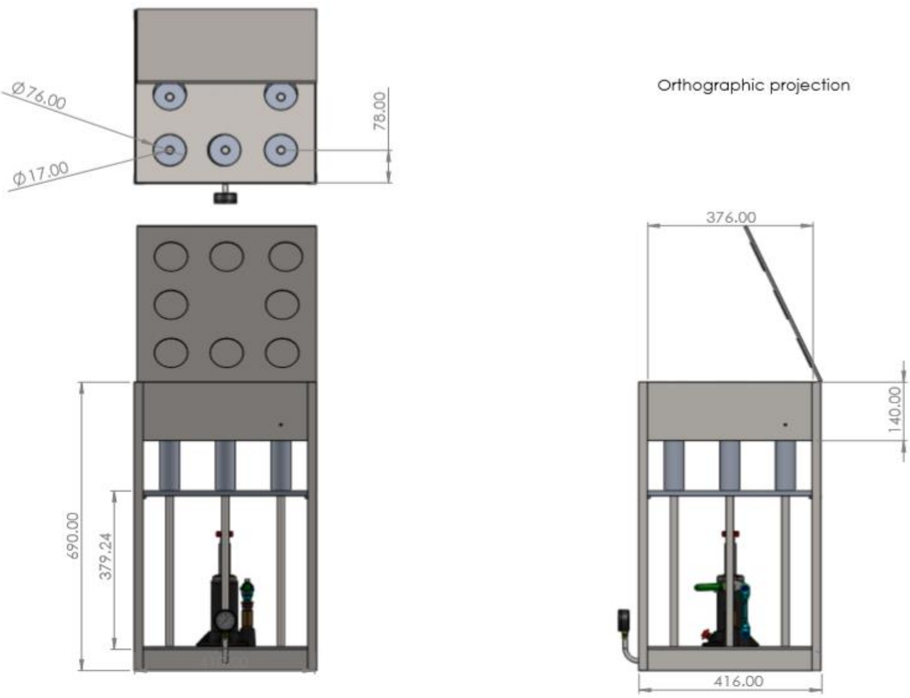

Figure 2: Orthographic view of developed multi-piston binderless briquetting machine

Figure 3: The pictorial view multi-piston binderless briquetting machine

Operation of the briquetting press and briquette production process

Pressure needed to compress the materials was provided by the thrust action of the hydraulic jack. The mould was heated by electrical heater bands and regulated at the required temperature by a thermocouple through a temperature controller which was switched on. Upon attaining the required temperature, the cover plate was opened and the mixed material to be briquetted was loaded into the mould, the hydraulic jack piston being at the lowest level at the bottom end of the mould. After the material was placed in the mould, the cover was closed and fastened in place and the hydraulic jack was made to compress to the required pressure. The setup was held for the required hold time after which the cover plate was opened and the hydraulic jack thrust further to eject the formed briquette from the mould. The briquette was formed in the cylindrical mould having a central hole of which according to Chaney (2009); Kpalo *et al*. (2020) and Inuwa *et al*. (2023), increases porosity and oxygen supply, thereby improving briquette combustion.

Design of Experiment

Taguchi fractional factorial method of Design of experiment was employed, using Minitab 17 software; four independent variables or factors at three levels; moulding temperature (250 ^{0}C, 270 ^{0}C and 290 ^{0}C), moulding pressure (46 MPa, 56 MPa and 66 MPa), composition of polyethylene (10 %, 20 % and 30 %) and dwell time (60 seconds, 180 seconds and 300 seconds) were considered. Calorific value, percentage moisture content, percentage volatile matter, percentage ash content, percentage fixed carbon are the responses. These variable factors and their levels are shown in Table 2, while the experimental orthogonal array is shown in Table 3.

Table 2: Variable briquetting factors and their levels

Factor	Level 1	Level 2	Level 3
Temperature (^{0}C)	250	270	290
Pressure (MPa)	46	56	66
Composition of Polyethylene (%wt.)	10	20	30
Dwell Time (seconds)	60	180	300

Table 3: Taguchi L27 orthogonal array

Run	MT	MP	COP	DT
1	250	46	10	60
2	250	46	10	60
3	250	46	10	60
4	250	56	20	180
5	250	56	20	180
6	250	56	20	180
7	250	66	30	300
8	250	66	30	300
9	250	66	30	300
10	270	46	20	300
11	270	46	20	300
12	270	46	20	300
13	270	56	30	60

14	270	56	30	60
15	270	56	30	60
16	270	66	10	180
17	270	66	10	180
18	270	66	10	180
19	290	46	30	180
20	290	46	30	180
21	290	46	30	180
22	290	56	10	300
23	290	56	10	300
24	290	56	10	300
25	290	66	20	60
26	290	66	20	60
27	290	66	20	60

Experimental Determination of the calorific value and proximate analysis results of produced Briquettes

Oxygen bomb calorimeter (Model 6100) manufactured by Parr Instrument Co., Moline, Illinois), was used to determine the calorific value of the produced briquettes using standard procedure as outlined in ASTM D5865.

Moisture content was determined according to ASTM D3172 standard and calculated as follows;

$$\% \text{ Moisture} = \frac{\text{Loss in weight due to moisture}}{\text{initial weight of fuel taken}} \times 100 \quad (16)$$

$$\% \text{ Moisture} = \frac{m - m1}{m} \times 100 \quad (17)$$

Where m = initial weight of fuel sample and m_1 = final weight of sample

Volatile matter was determined using ASTM D3172, and calculated as follows;

$$\% \text{ Moisture} = \frac{\text{Loss in weight due to volatile matter}}{\text{initial weight of fuel taken}} \times 100 \quad (18)$$

$$\% \text{ Moisture} = \frac{m1 - m2}{m} \times 100 \quad (19)$$

Where m = initial weight of fuel sample, m_1 = final weight of sample after removal of moisture and m_2 = weight of sample after removal of volatile matter

Ash content was determined according to ASTM D3172 standard.

It was then calculated as;

$$\% \text{ Ash} = \frac{\text{weight of ash left}}{\text{initial weight of fuel taken}} \times 100 \quad (20)$$

$$\% \text{ Ash} = \frac{m3}{m} \times 100 \quad (21)$$

Where m_3 = weight of residue left

m = initial weight of fuel sample

Fixed carbon was obtained as; Fixed Carbon = 100 % - (% Moisture + % Volatiles + % Ash)

RESULTS AND DISCUSSION

A set of formed briquettes in the machine is shown in figure 4, while the dried briquettes are shown in figure 5.

Figure 4: Formed briquettes

Figure 5: Dried briquette

The initial, compressed and relaxed densities of the formed or produced briquettes by the developed multi piston binderless briquetting machine are depicted in Table 4.

Table 4: Initial, Compressed and relaxed densities of formed briquettes

Run	Moulding Temperature (^{0}C)	Pressure (MPa)	Composition of Polyethylene (%w)	Dwell Time (s)	Initial Density (kg/m^3)	Compressed Density (kg/m^3)	Relaxed Density (kg/m^3)
1	250	46	10	60	250	461	432
2	250	46	10	60	250	477	437
3	250	46	10	60	250	463	435
4	250	56	20	180	246	496	450

5	250	56	20	180	246	488	447
6	250	56	20	180	246	498	451
7	250	66	30	300	250	545	516
8	250	66	30	300	250	572	512
9	250	66	30	300	250	551	517
10	270	46	20	300	246	577	541
11	270	46	20	300	246	587	545
12	270	46	20	300	246	568	539
13	270	56	30	60	250	490	467
14	270	56	30	60	250	493	470
15	270	56	30	60	250	488	464
16	270	66	10	180	250	485	476
17	270	66	10	180	250	494	480
18	270	66	10	180	250	478	485
19	290	46	30	180	250	548	535
20	290	46	30	180	250	553	537
21	290	46	30	180	250	541	532
22	290	56	10	300	250	529	525
23	290	56	10	300	250	533	527
24	290	56	10	300	250	526	521
25	290	66	20	60	246	503	496
26	290	66	20	60	246	511	498
27	290	66	20	60	246	501	495

Table 4 shows the result of the initial density of the materials before briquetting, the compressed or maximum density of the briquettes which is the density immediately after the removal of briquettes from the mould, and the relaxed density which is the density after the briquettes have remained stable. The biomass waste with 10% polyethylene waste had density of 250 kg/m^3, 20% polyethylene had density of 246 kg/m^3 and 30% polyethylene had 250 kg/m^3 density. Bulk densities of the briquettes produced by Agidi *et al.* (2017) varied widely with rice husk recording lowest value of 2.5 kg/m^3 and saw dust the highest value of 5.2 kg/m^3, which lower than the bulk densities of materials in this work.

The compressed densities of the manufactured briquettes ranged from 461 kg/m^3 to 587 kg/m^3, while the relaxed densities were in the range of 432 kg/m^3 to 545 kg/m^3, which is lower than the densities range of 570 to 1300 kg/m^3 obtained for corncob briquettes by Orisaleye *et al*. (2018), or 518.85 and 823.86 kg/m^3 for sawdust briquettes obtained by Orisaleye *et al*. (2022).

This is because external binders were not added and Chaney (2010) reported that when high amount of binder is utilised in producing briquette, it will result in the briquette having high relaxed briquette density. Also, larger particle sizes of materials that passed through sieve of mesh size 6.3 mm were utilised and particle size influences density of briquettes, smaller (finer) particles results in more dense packing of particles and harder briquettes, than those from medium-sized particles according to Ndindeng *et al*. (2015). But the inherent binder of the biomass released when heated to a temperature above 130 ^{0}C in this work and the addition of polyethylene, produced briquettes that are capable of withstanding rough handling. The calorific value and proximate analysis results of the produced briquettes by the developed multi piston binderless briquetting machine is depicted in Table 5.

Table 5: Calorific Value and Proximate analysis results of produced Briquettes

Run	MT (^{0}C)	MP (MPa)	COP (%)	DT (s)	CV (MJ/Kg)	PMC	PVM	PAC	PFC
1	250	46	10	60	22.2721	0.26	74.54	16.32	8.88
2	250	46	10	60	22.6132	2.01	73.32	9.12	15.55
3	250	46	10	60	23.0722	1.04	74.33	11.31	13.32
4	250	56	20	180	26.1164	0.04	73.02	7.83	19.11
5	250	56	20	180	25.6381	0.71	75.11	5.23	18.95
6	250	56	20	180	26.0834	1.32	73.73	5.17	19.78
7	250	66	30	300	21.2271	0.46	73.00	9.01	17.53
8	250	66	30	300	22.1673	2.21	72.16	7.23	18.40
9	250	66	30	300	20.8482	4.11	74.06	8.55	13.28
10	270	46	20	300	25.8729	0.34	74.40	11.71	13.55
11	270	46	20	300	26.3162	0.31	73.42	9.48	16.79
12	270	46	20	300	24.5212	3.21	74.84	8.65	13.30
13	270	56	30	60	21.3465	0.14	74.78	4.74	20.34
14	270	56	30	60	21.5772	0.77	75.36	3.47	20.40
15	270	56	30	60	20.7973	2.78	74.32	2.77	20.13
16	270	66	10	180	23.7812	0.86	73.18	10.95	15.01
17	270	66	10	180	22.4316	1.77	73.07	9.26	15.90
18	270	66	10	180	23.3561	2.32	72.68	8.53	16.47

19	290	46	30	180	23.2882	0.06	73.88	19.07	6.99
20	290	46	30	180	23.6173	0.62	73.27	17.24	8.87
21	290	46	30	180	22.8773	3.78	73.43	16.06	6.73
22	290	56	10	300	23.2121	1.22	73.32	7.76	17.70
23	290	56	10	300	24.4435	0.33	74.28	6.26	19.13
24	290	56	10	300	23.0072	4.24	71.63	7.48	16.65
25	290	66	20	60	23.2089	2.38	72.72	22.00	2.90
26	290	66	20	60	20.7522	1.54	73.16	20.78	4.52
27	290	66	20	60	21.5328	2.23	73.33	19.85	4.59

CV-Calorific Value, PMC- percentage moisture content, PVM- percentage volatile matter,
PAC- percentage ash content, PFC- percentage fixed carbon

Table 5 shows results of calorific values of the briquettes, proximate analysis result (percentages of moisture, volatile matter, ash and fixed carbon). The least calorific value was 20.7522 MJ/Kg while 26.3162 MJ/kg was the highest calorific value. Romallosa and Kraft, (2017) had stated that for fuel briquettes to maintain combustion, it need to have heating value of about 11.66 MJ/kg. The minimum calorific value requirement for Commercialisation of briquette is (>17500 J/g), as stated by DIN 51731 (Oyelaran *et al.*, 2018; Kaur *et al*., 2017; Faizal *et al*., 2016; Huko *et al*., 2015; Emerhi, 2011), while for EN*plus* standard it is 16.6 MJ/kg (Marreiro *et al*., 2021). The value of calorific values obtained well satisfied these standard requirements, and were higher than experimental values of calorific values obtained by most researchers who utilized only biomass wastes or with the addition of some plastics such as 15.34 -16.82 MJ/kg for sawdust, 17.96 -18.34 MJ/kg for palm kernel shell and 15 MJ/kg-16.89 MJ/kg at a fixed pressure of 1177 N/cm^2 and 17.20 MJ/kg for varying compositions and pressure, better quality briquette of sawdust/palm kernel shell reported by Essien *et al.* (2018), or 16.6 –20.8 kJkg^{-1} Net Calorific Value (NCV) reported by Garrido *et al.* (2017), where two Wastes from Electrical Electronic Equipment (WEEE) plastics (halogen-free wire and print circuit board (PCB) and Automotive Shredder Residues (ASR), were added to sawdust and palm trunk to produce briquettes at different plastic wastes proportions (10–30%), pressures (22–67 MPa) and temperatures (room–130 ^{0}C). The least value of moisture content was 0.04% and 4.24% being the highest. The volatile matter values were between 71.63 and 75.36% while the percentage ash content obtained ranged from 2.77 to 22.00%. Emerhi (2011) reported a general average of 19.99±4.12% ash content, those produced with wood ash as binder had ash content (28.13±0.37), 16.94±2.55% with starch as binder and (14.89±0.05%) with cow dung as binder. Fixed carbon obtained were in the range of 2.90 and 20.40

CONCLUSION

Briquetting machine that can be used to produce briquettes from combination of biomass wastes and polyethylene as additives without the addition of external binder but exploiting the property of the biomass material to release lignin when heated and also the polyethylene, was designed, fabricated and tested. The production of the briquettes followed experimental run designed via Taguchi fractional factorial method using Minitab 17 software. Factors that affects the qualities of produced briquettes varied were moulding temperature, moulding pressure, percentage composition of polyethylene and dwell time, while material particle size and water added were maintained constant. The qualities measured from the briquettes were compressed and relaxed densities, calorific value, percentage moisture content, percentage volatile matter and percentage ash content. Bulk density results of mixed material was in the range of 246 to 250 kg/m^3, compressed density ranged from 461 kg/m^3 to 587 kg/m^3, while the relaxed densities were in the range of 432 kg/m^3 to 545 kg/m^3. Calorific value obtained were in the range 20.7522 MJ/Kg to 26.3162MJ/kg, which were more than values obtained by other researcher who utilised biomass wastes and actually measured calorific value experimentally, not using numeric formulae. Moisture content of briquettes ranged from 0.04% to 4.24%, volatile matter range was 71.63% to 75.36%, ash content ranged from 2.77% to 22% and fixed carbon was 2.90% to 20.40%. This work has shown that high calorific solid fuel can be produced from combination of biomass and polyethylene wastes without the addition of external binder that can provide substitute to the depleting fossil fuels and fuelwood, for heating and cooking.

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